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Title: Development of a High-Energy Neutron Sniffer and Subsequent Dose Quantification for High-Energy Particle Accelerator Shielding Surveys

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Development of a High-Energy Neutron Sniffer and Subsequent Dose Quantification for High-Energy Particle Accelerator Shielding Surveys

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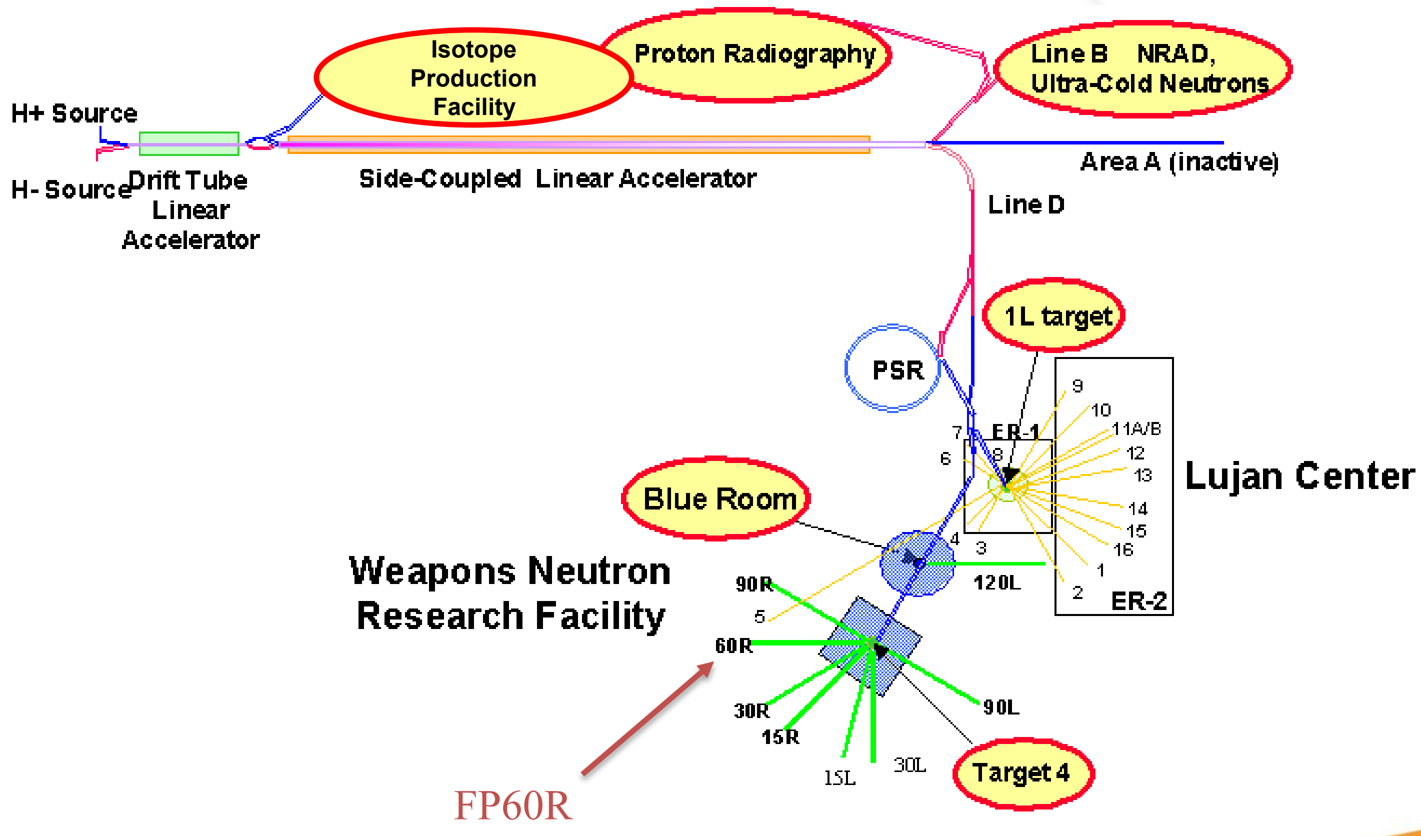
Outline

1. Introduction
2. LANL Instruments Review
3. Research Objectives
4. Sniffer Probes
5. Plastic Scintillators
6. Field Measurements
7. Conclusions and Future Work

Introduction

Los Alamos Neutron Science Center (LANSCE)



Introduction Cont.

- HPI Model 2080B (Albatross)
  - 10” poly pseudo-sphere
  - Uses 2 GM tubes
    - One wrapped in silver, the other in tin
  - Detects neutrons up to 10 MeV
  - Weighs 25 lbs
  - Used as an area monitor, not for surveys

LANL Instrumentation Review

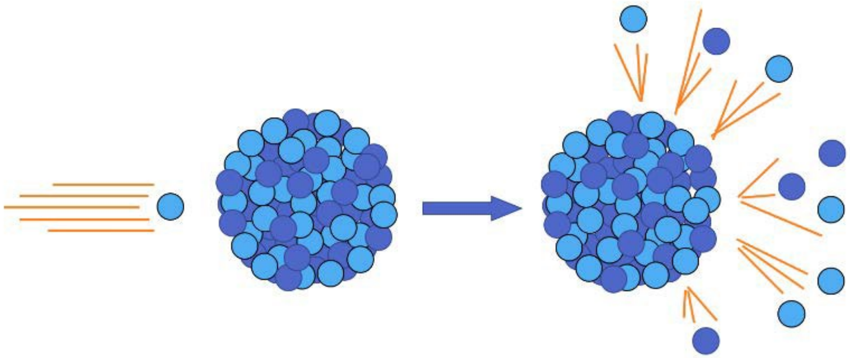
Neutron Energy Definitions

For the purpose of this research, the following definitions apply:

- Slow neutrons: $E < 0.5$ eV
- Fast neutrons: 0.5 eV $< E < 20$ MeV
- High-energy neutrons: $E > 20$ MeV

Relevant Neutron Interactions

- Spallation
  - Light particle (neutron, proton) with high-energy interacts with a heavy nucleus (tungsten, lead)
  - LANSCE: 13.3 spallation neutrons created per beam particle



Other Neutron Instruments Available/Developed at LANL

NRD-1

Eagle Rem Meter

WENDI-II Rem Meter

CHELSI

Research Objectives

LANL's deployed neutron detection systems are essentially blind to neutrons above 20 MeV. The intention of this research is to fill this gap by developing two interdependent neutron detection systems, one for the detection, or 'sniffing', of high-energy neutrons and one for dose quantification.

Research Objectives Cont.

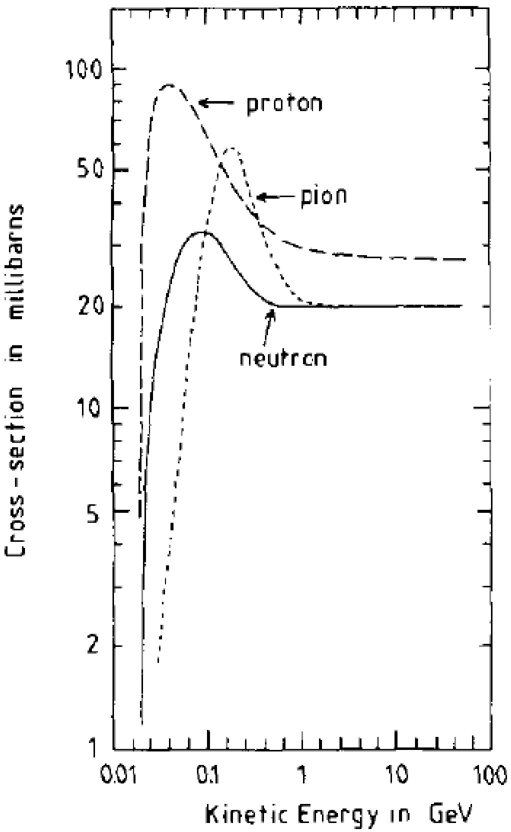
Neutron Sniffer

- Qualitative instrument used for shielding surveys
  - Should be lightweight and portable
- Use a high atomic mass, high density material (i.e., CsI(Tl))
  - Will create and measure spallation products when exposed to high-energy neutrons
- Apply a very high pulse-height threshold to reduce ambient background and lower energy radiation response
- Compare response to commonly used NaI(Tl) response

Research Objectives Cont.

Dose Quantification

- Utilize $^{12}C(n,2n)^{11}C$ reaction in plastic scintillators
  - Reaction has a 20.4 MeV threshold
  - One of the most reliable methods for measuring fluence and dose equivalent from high-energy neutrons
  - Effective cross section of 22 mb for all energies at and above 20 MeV



Sniffer Probes

Inorganic Scintillation Probes

- Four different probes were paired with Eberline E600 ratemeters.
  - 2x2 CsI(Tl)
  - 1x1 CsI(Tl)
  - 2x2 NaI(Tl)
  - 1x1 NaI(Tl)

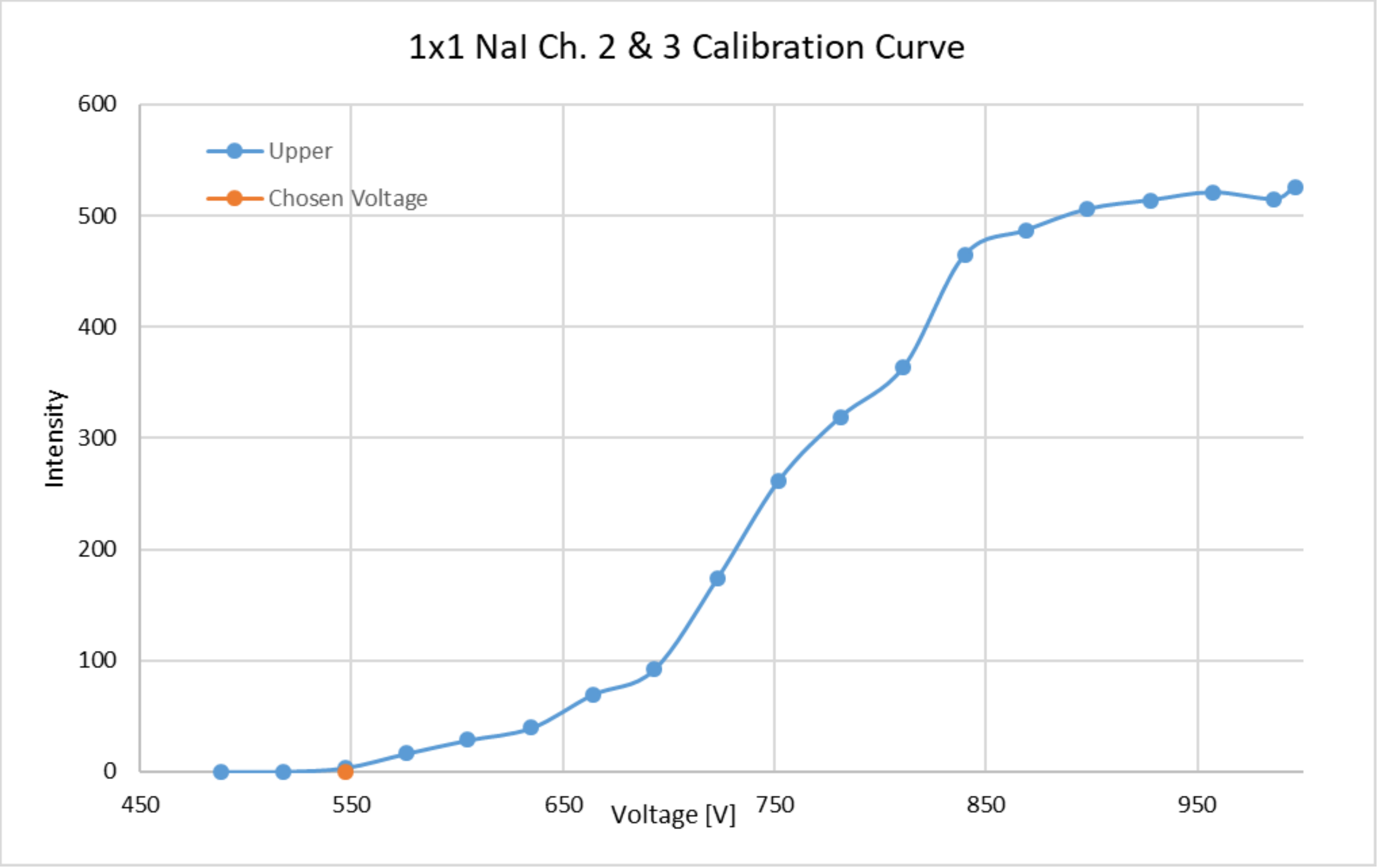
- Weights
  - 2x2: 6.2 lbs
  - 1x1: 4.4 lbs

Sniffer Probe Channel Settings

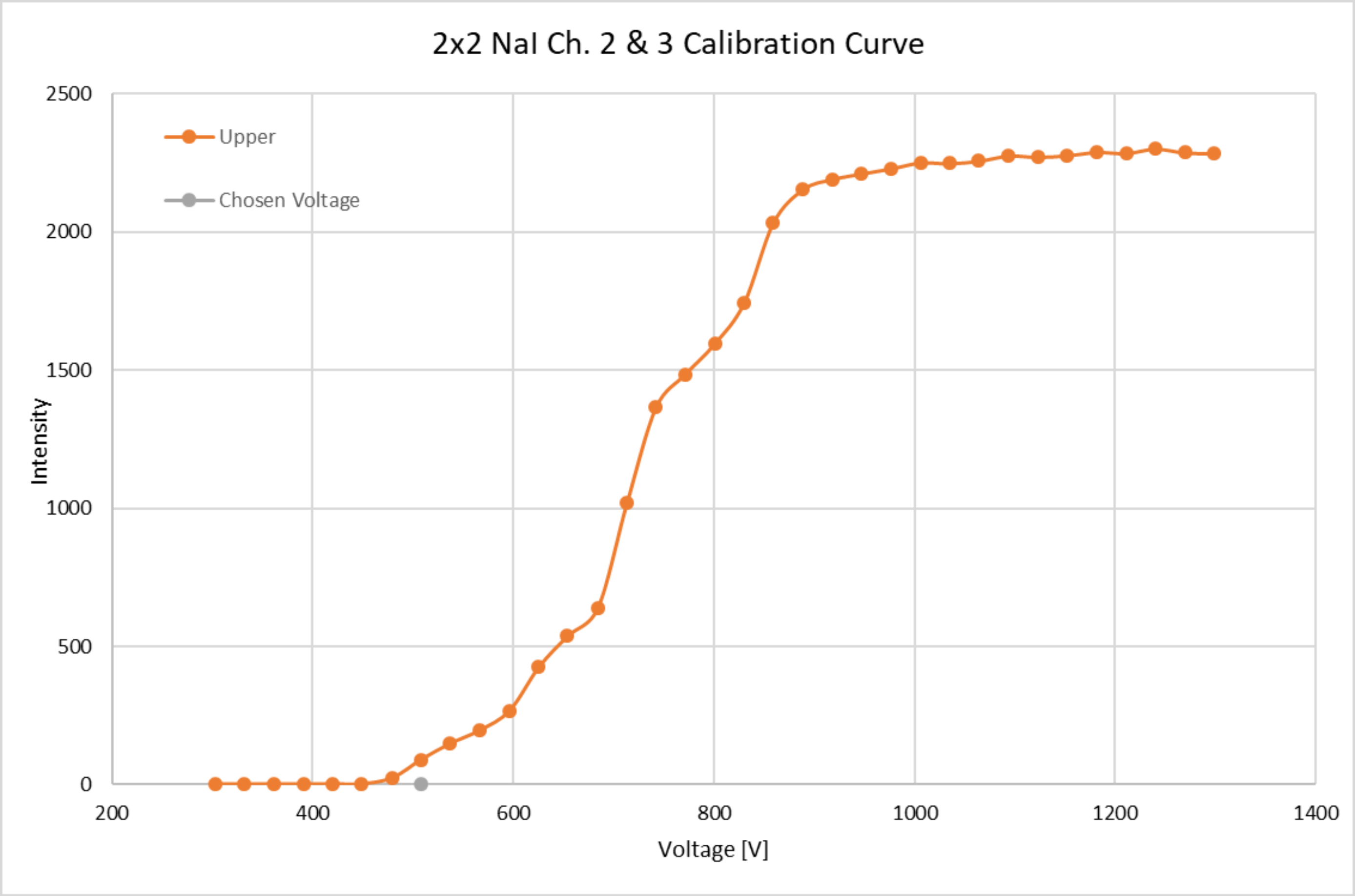
Channel #	Calibration Source	Lower Threshold [mV]	Upper Threshold [mV]	Counting Window	Gross counting threshold
1	^{241}Am	3	20*	Both	60 keV
2	^{208}Tl	5.1*	20	Upper	2.6 MeV
3	^{208}Tl	5.1*	60	Upper	7.8 MeV

*Parameters are arbitrary

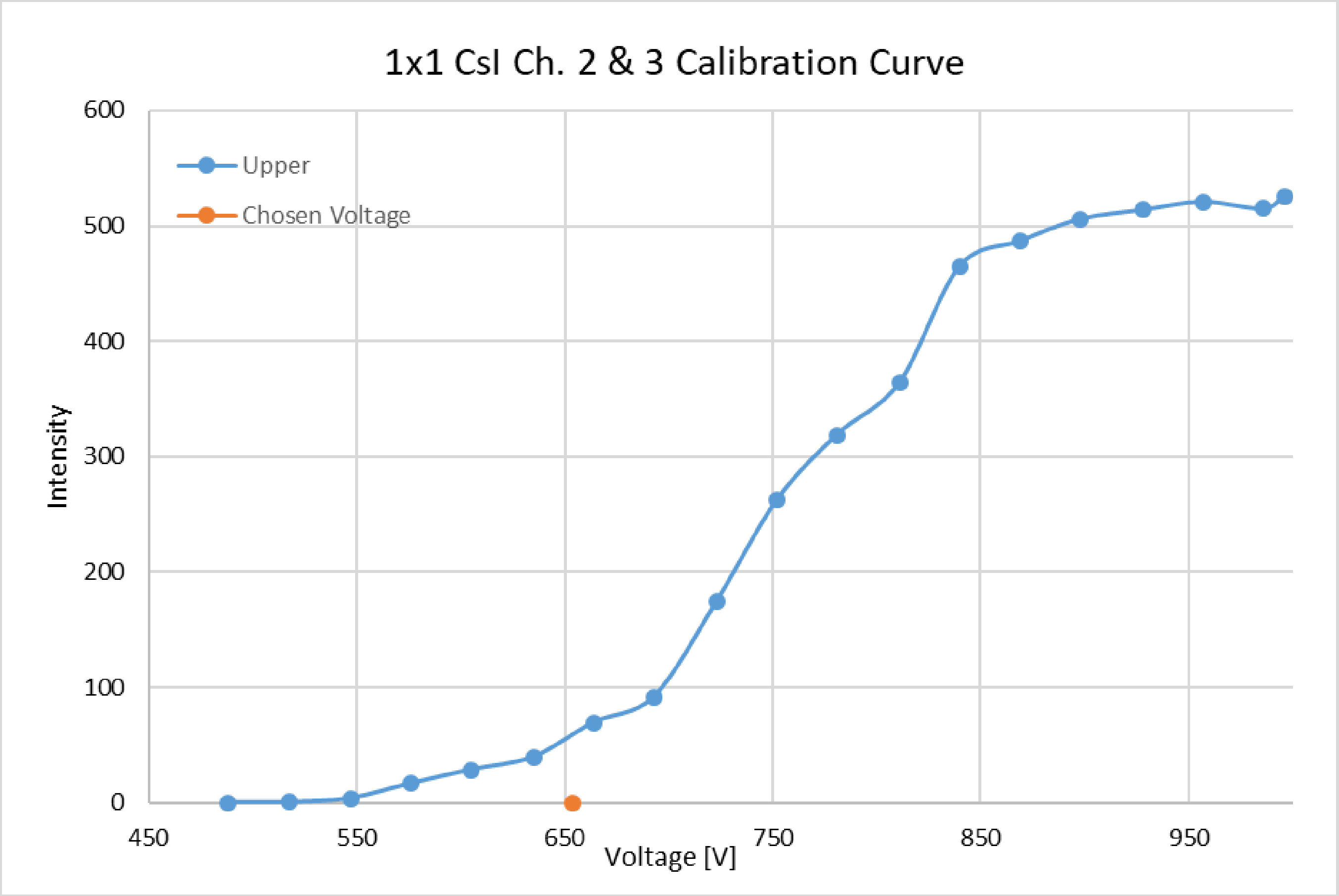
1x1 NaI(Tl) Voltage Curve



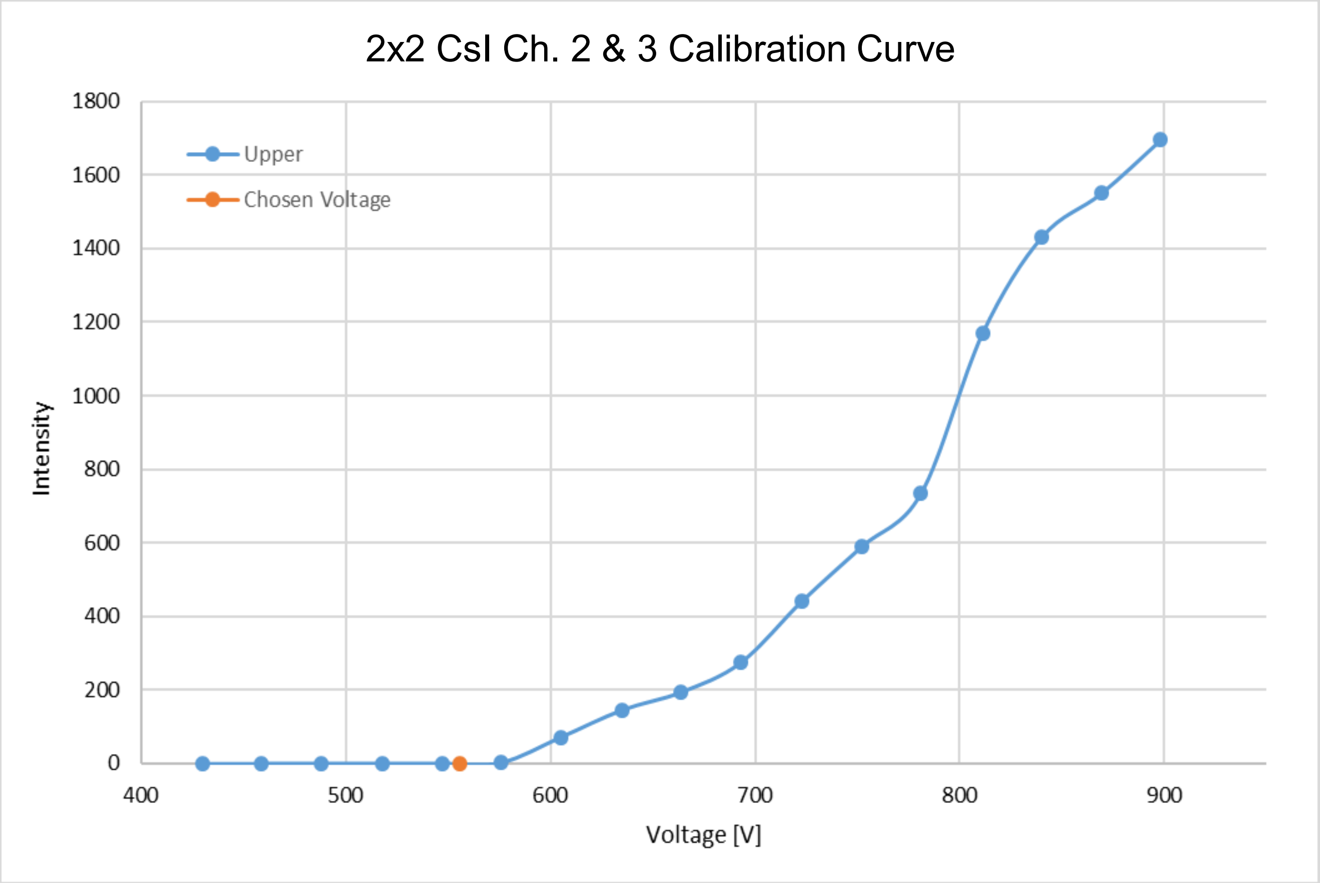
2x2 NaI(Tl) Voltage Curve



1x1 CsI(Tl) Voltage Curve



2x2 CsI(Tl) Voltage Curve



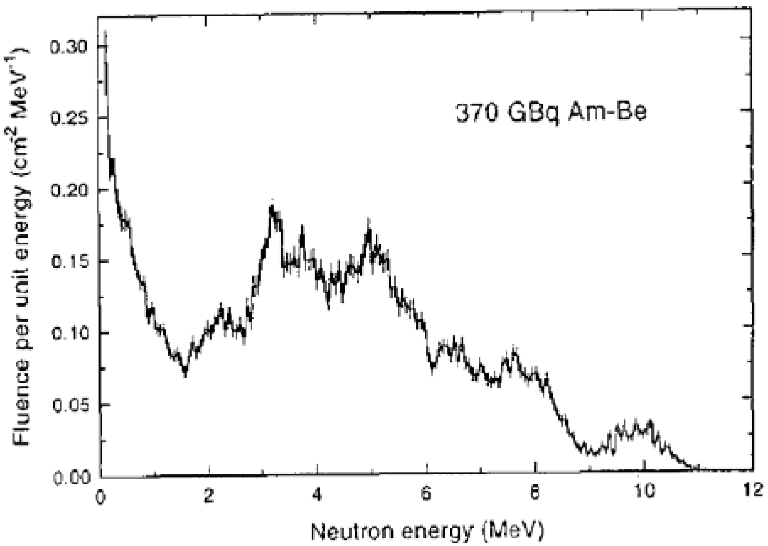
Background and Source Comparison

Background Measurements			
Detector ID	**Ch. 1 [cpm]**	**Ch. 2 [cps]**	**Ch. 3 [cps]**
2x2 NaI	11.1k	2.5	1
2x2 CsI	11.7k	1.5	1
1x1 NaI	1.7k	0.5	0.8
1x1 CsI	2.5k	0.6	0.2

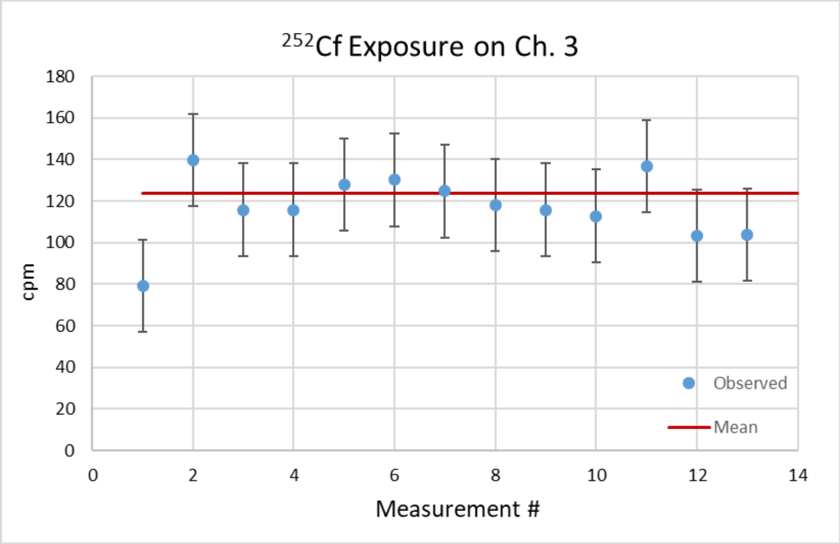
Cobalt-60 Measurements			
Detector ID	**Ch. 1 [cpm]**	**Ch. 2 [cps]**	**Ch. 3 [cps]**
2x2 NaI	190k	27.5	1
2x2 CsI	63k	0.7	0.6
1x1 NaI	74k	0.8	0.3
1x1 CsI	222k	1.5	1.4

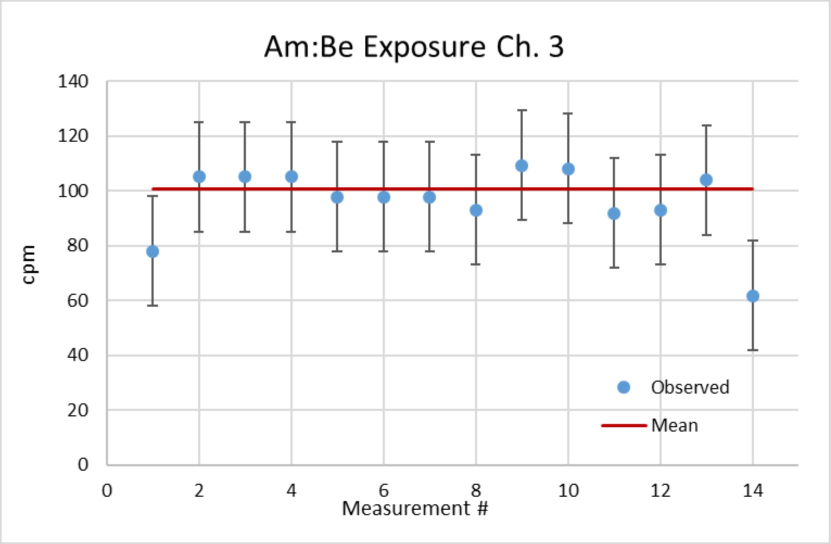
Neutron Calibration Sources

- ^{252}Cf source
  - 17.47 mCi
  - ~ 1% of neutron emissions with energies of 7+ MeV
  - ~ 0.5% of neutron emissions with energies of 8+ MeV
- Am:Be source
  - 12 Ci
  - Neutron emission peak centered at 10 MeV

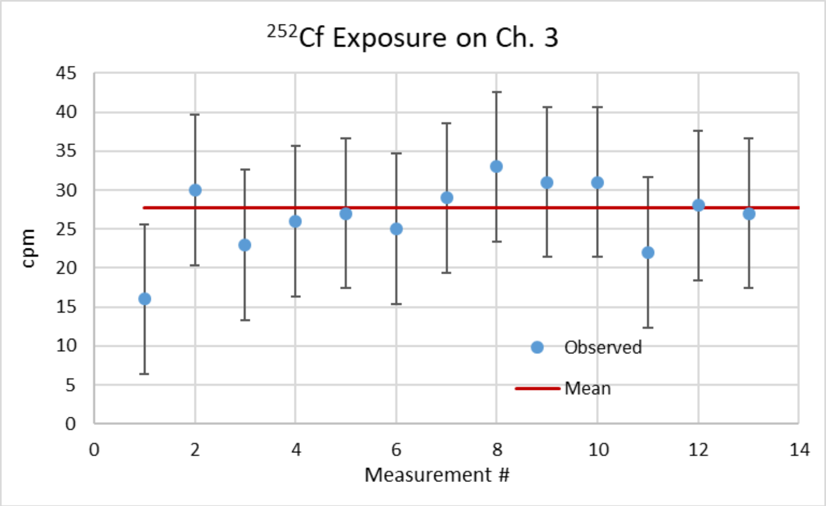


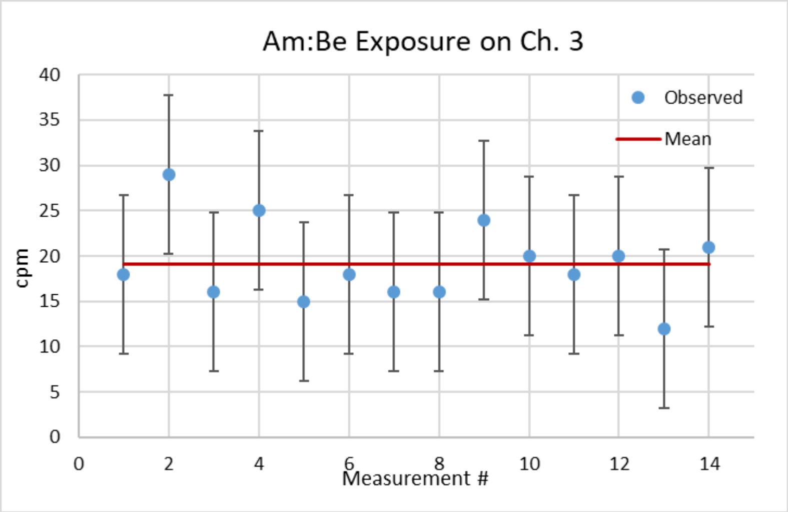
2x2 CsI(Tl) Neutron Source Exposures



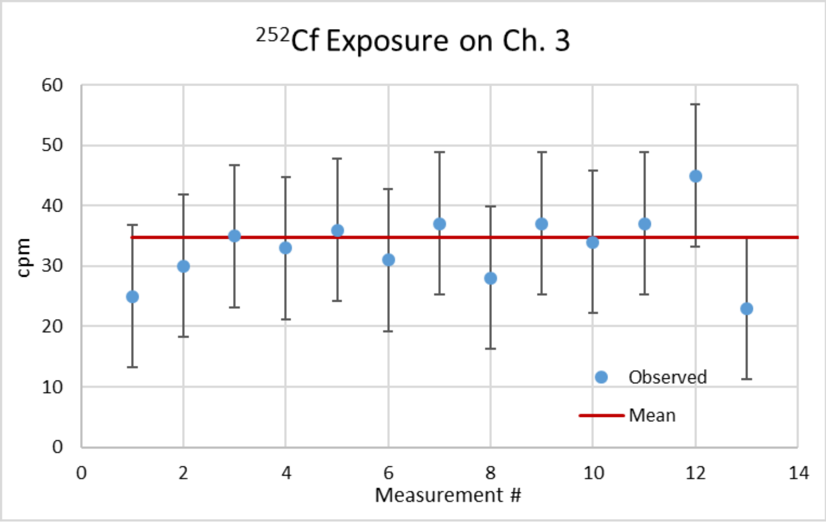


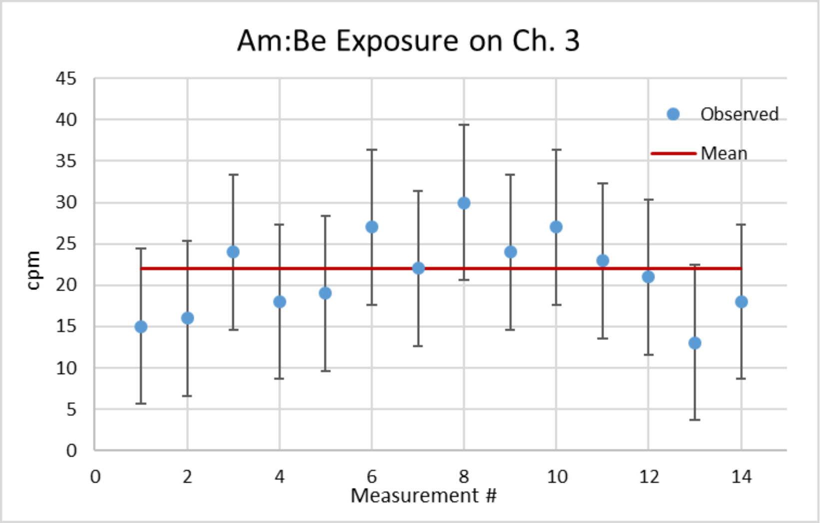
1x1 CsI(Tl) Neutron Source Exposures



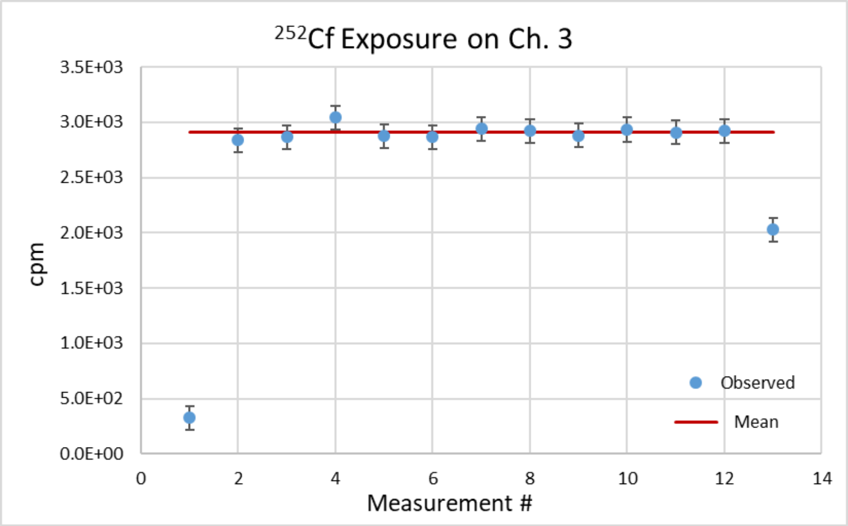


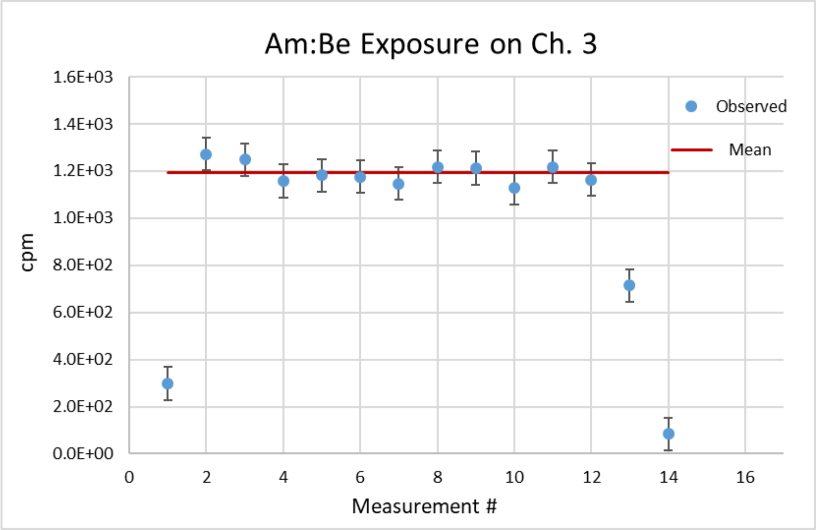
1x1 NaI(Tl) Neutron Source Exposures



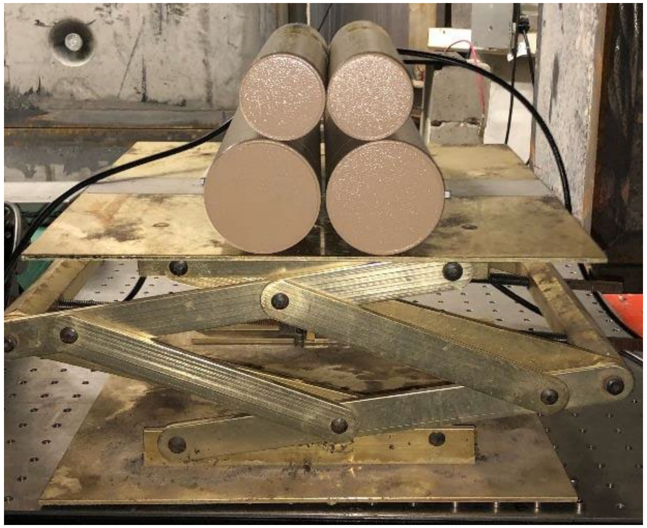


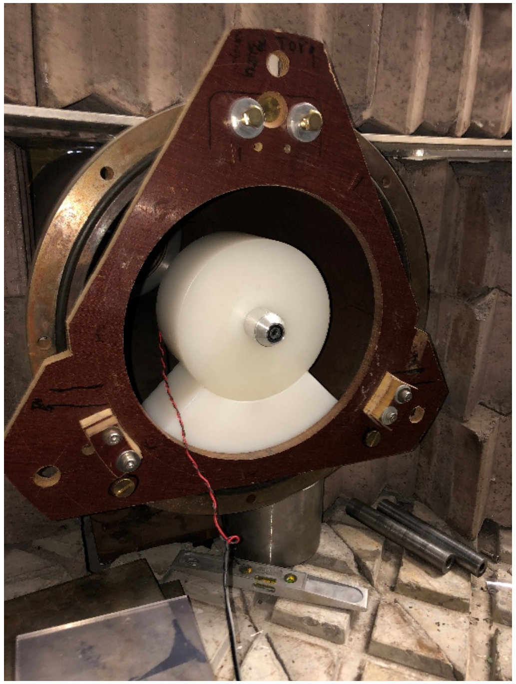
2x2 NaI(Tl) Neutron Source Exposures



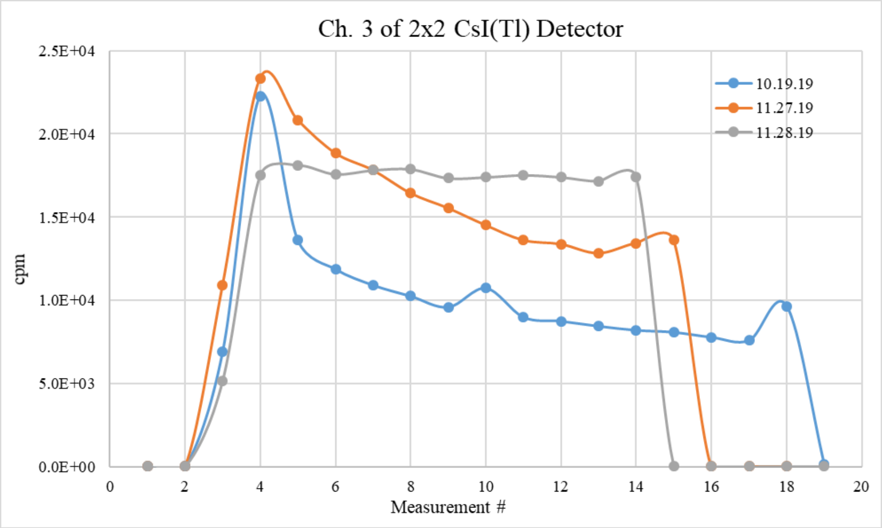


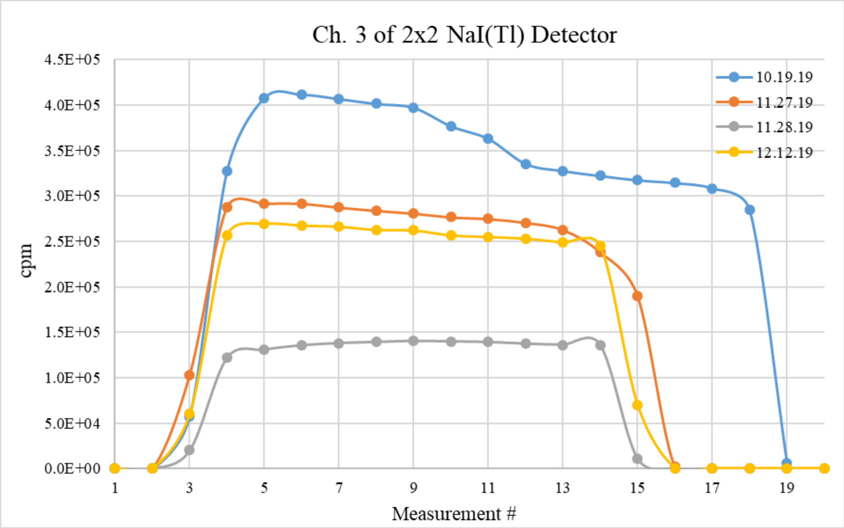
FP60R Sniffer Probes Setup



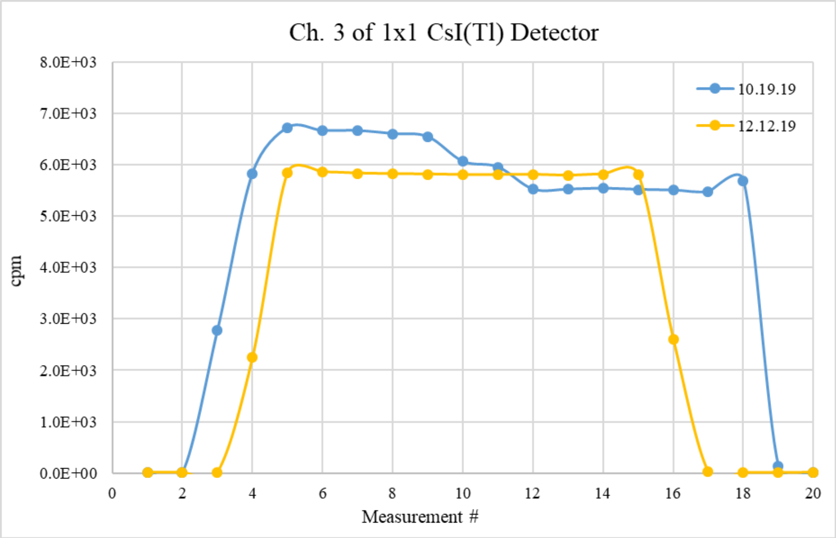


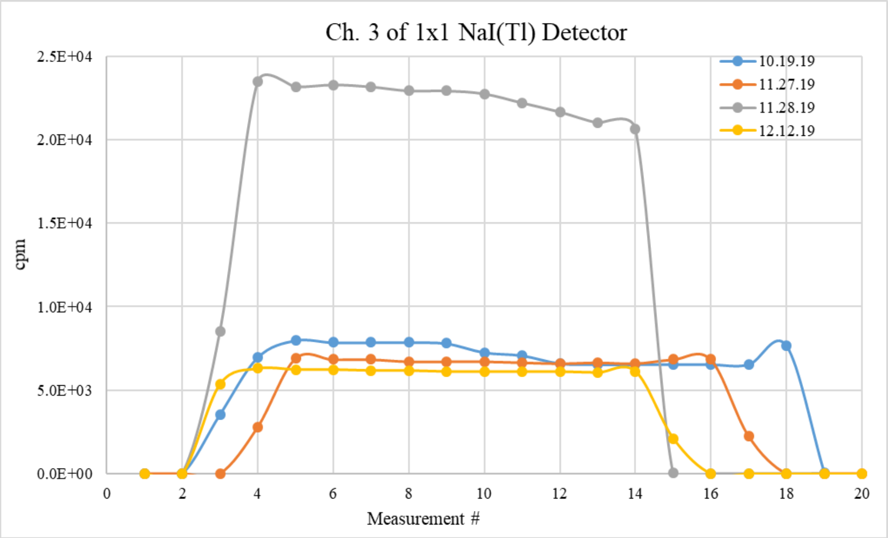
2x2 Probe WNR Exposures





1x1 Probe WNR Exposures

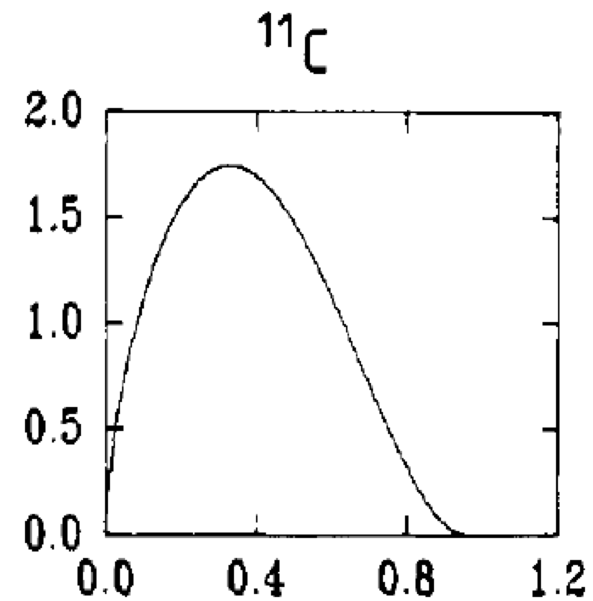




Plastic Scintillators

$^{12}C(n,2n)^{11}C$ Reaction

- Reaction has a neutron energy threshold of 20.4 MeV
- Effective cross section of 22 mb for neutron energies ≥ 20 MeV
- ^{11}C decays by β^+ emission
  - 0.96 MeV maximum energy
  - 0.386 MeV average energy
- 20.34 minute half-life



Fluence to Dose Equivalent

- Fluence rate (φ) is related to the ^{11}C producing reaction rate (R_x) inside the plastic scintillator.

$$R_x(rxns/cm^3 \cdot s) = \varphi(\frac{n}{cm^2 \cdot s}) * \sigma(cm^2) * \rho_A(\frac{atoms}{cm^3})$$

ρ_A = 4.7346x10^{22} atoms/cm^3 σ = 22 mb = 2.2x10^{-26} cm^2

$$\varphi\left(\frac{n}{cm^2 \cdot s}\right) = 9.94585\ x\ 10^{-3} * R_x(rxns/s)$$

Fluence to Dose Equivalent Cont.

$$\frac{dN_C}{dt} = R_x(rxns/cm^3 \cdot s) - \lambda(s^{-1})N_C(\text{atoms})$$

$$A(t) = R_x \cdot (1 - e^{-\lambda t})$$

$$A(t_i) = R_x \cdot (1 - e^{-t_i/\tau})$$

$$A(t) = R_x \cdot (1 - e^{-t_i/\tau}) \cdot (e^{-t_d/\tau}) \cdot \int_0^{t_c} e^{t/\tau} dt$$

$\tau = mean\ life$ t_i = irradiation time t_d = decay time t_c= 0 at start of count

Fluence to Dose Equivalent Cont.

$$N(counts) = \varepsilon \cdot R_x(1 - e^{-t_i/\tau}) \cdot (e^{-t_d/\tau}) \cdot \int_0^{t_c} e^{t/\tau}\, dt$$

$$N(counts) = \varepsilon \cdot R_x(1 - e^{-t_i/\tau}) \cdot (e^{-t_d/\tau}) \cdot \tau \cdot \left(1 - e^{-t_c/\tau}\right)$$

$$CF(dead\ time) = \frac{RT}{LT}$$

$$CF(efficiency) = \frac{C_{true}}{C_{observed}}$$

$$R_x(min^{-1}) = \frac{N(counts)}{\varepsilon \cdot \tau \cdot (1 - e^{-t_i/\tau}) \cdot (e^{-t_d/\tau}) \cdot \left(1 - e^{-t_c/\tau}\right)}$$

Fluence to Dose Equivalent Cont.

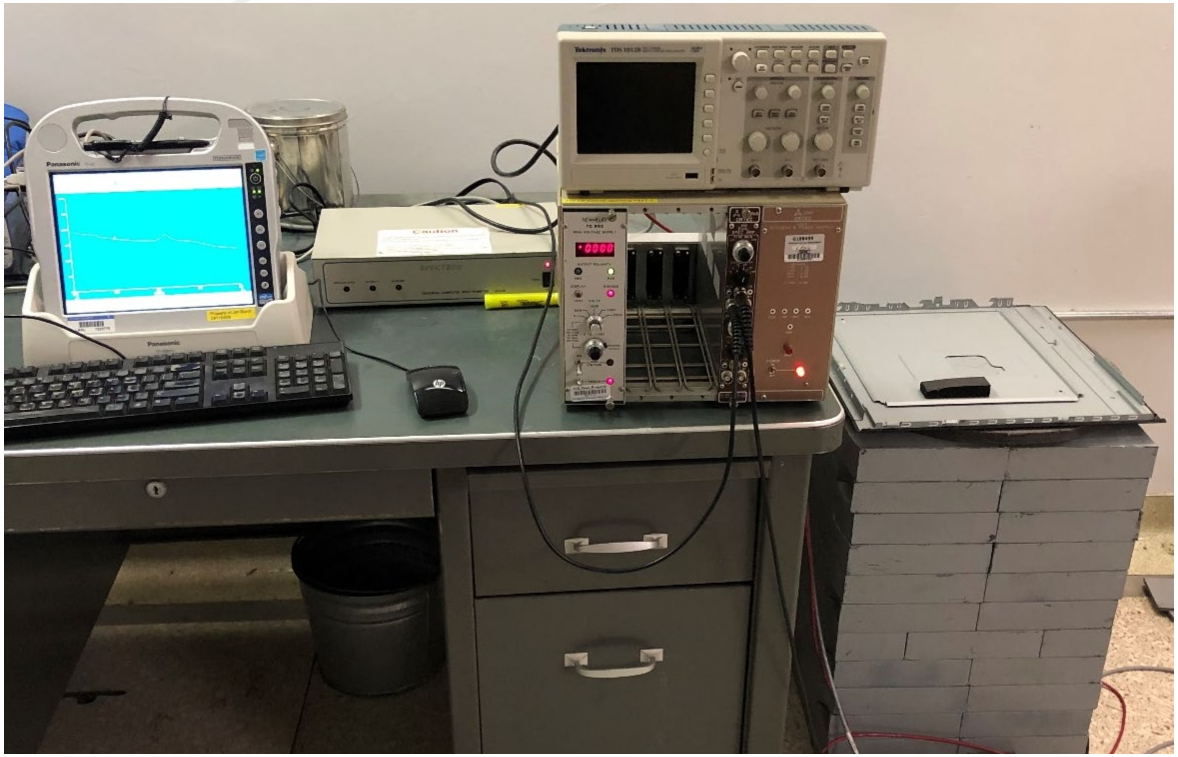
$$R_x(min^{-1}) = \frac{N(counts)}{\varepsilon \cdot \tau \cdot (1 - e^{-t_i/\tau}) \cdot (e^{-t_d/\tau}) \cdot (1 - e^{-t_c/\tau})}$$

$$\varphi\left(\frac{n}{cm^2 \cdot s}\right) = 9.94585\ x\ 10^{-3} * R_x(rxns/s)$$

$$DE\left({}^{mrem}/_{h}\right) = CF(mrem/h\ per\ n/cm^2 \cdot s) * \varphi\left({}^{n}/_{cm^2 \cdot s}\right)$$

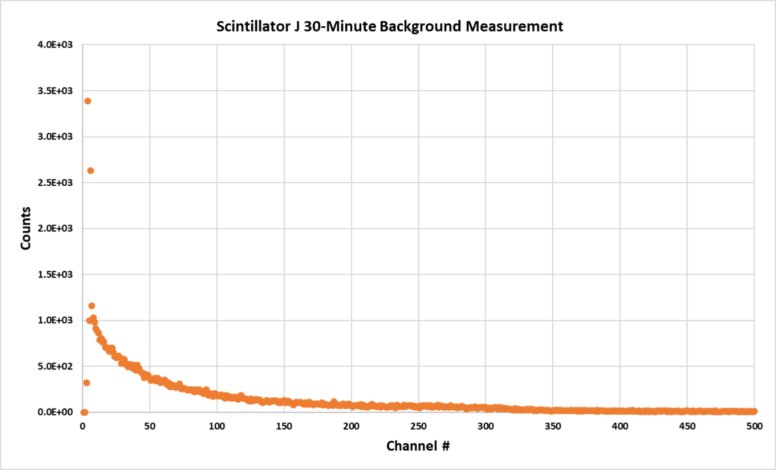
CF = 0.10 mrem/h per n/cm^2 s

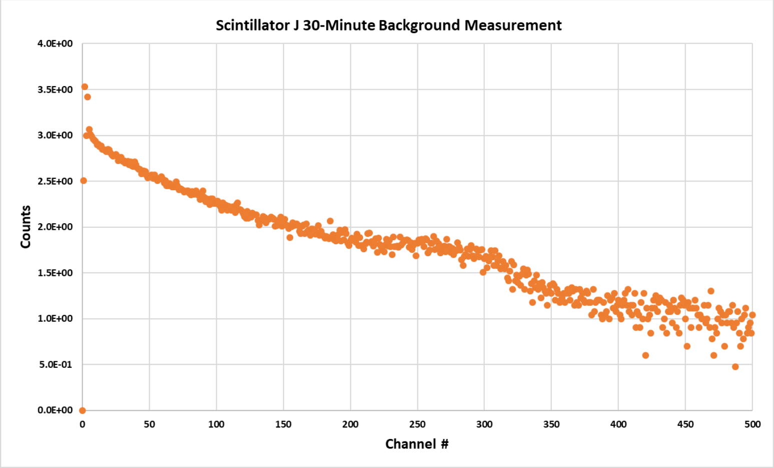
Counting System Setup



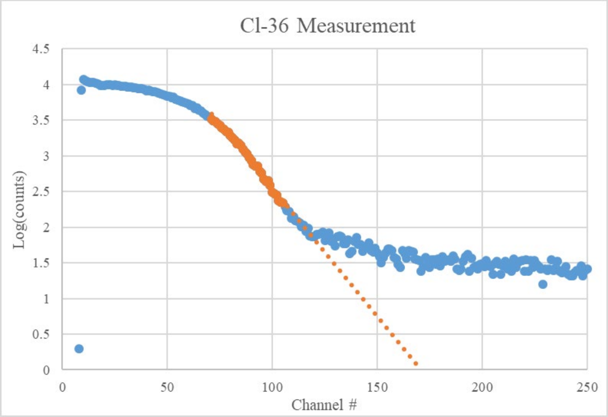
Plastic Scintillator Options

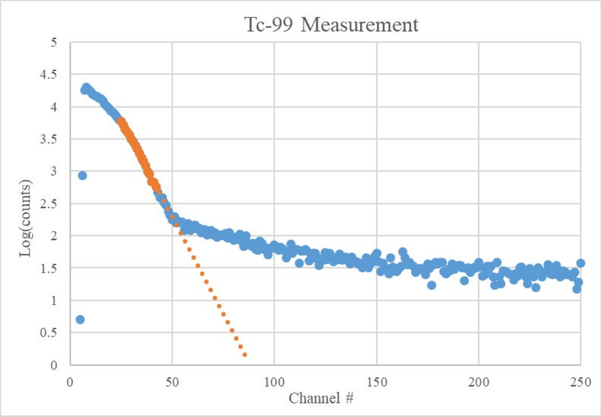
ID	Condition	Color
A	Clear	Yellow
B	Opaque	Yellow
C	Opaque	Yellow
E	Foggy	Colorless
F	Clear	Colorless
G	Clear	Colorless
H	Clear	Colorless
J	Clear	Colorless

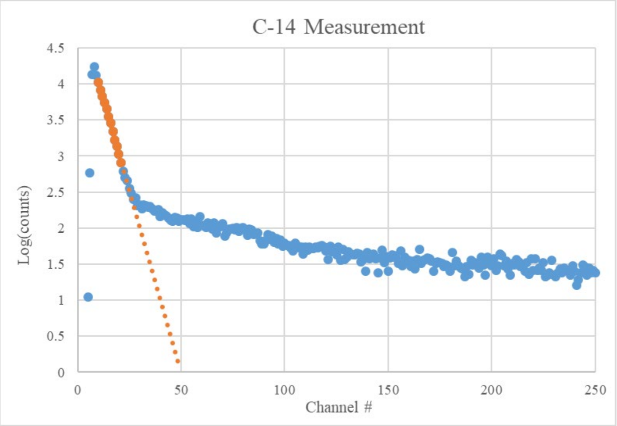




Counting System Zero Test

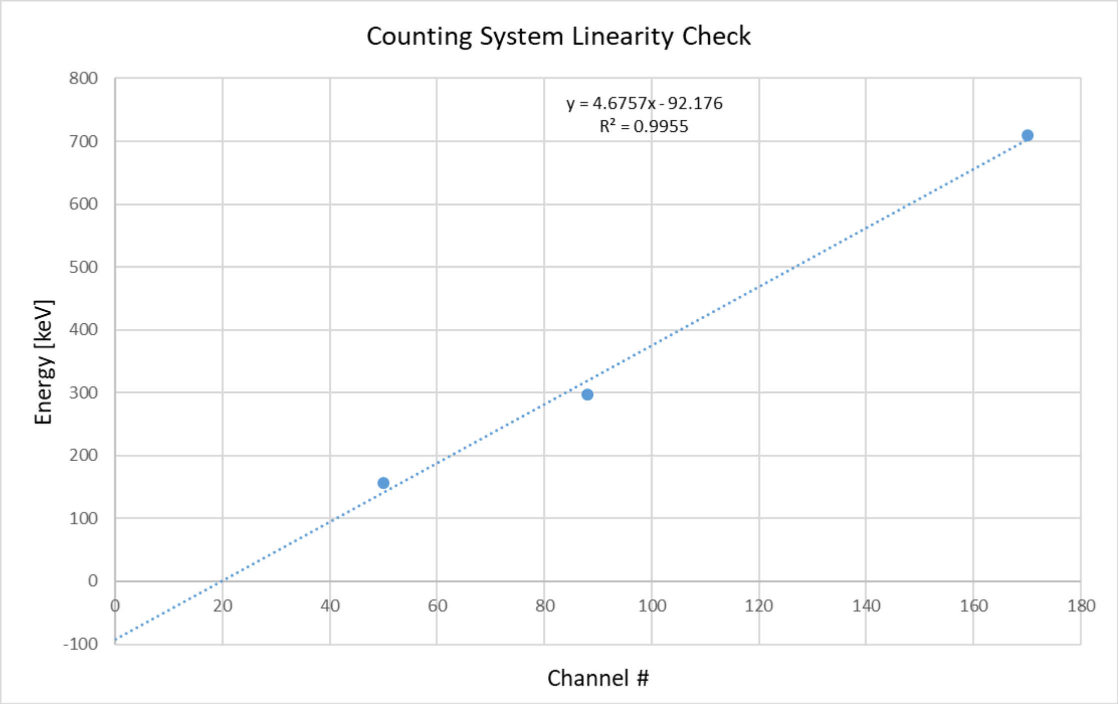






Isotope	Energy [keV]	Channel
^{14}C	156.5	50
^{99}Tc	297.5	88
^{36}Cl	709.6	170

Counting System Zero Test Cont.



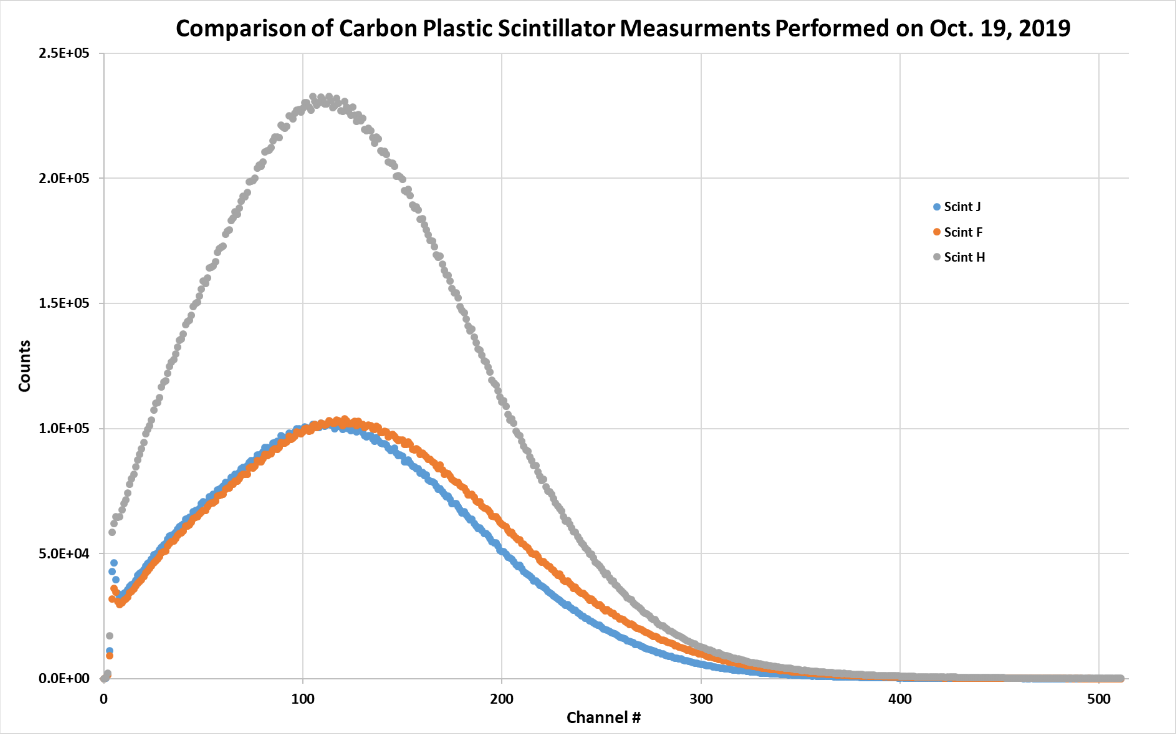
Isotope	Energy [keV]	Channel
^{14}C	156.5	50
^{99}Tc	297.5	88
^{36}Cl	709.6	170

$$energy\ [keV] = 4.6757x - 92.176$$

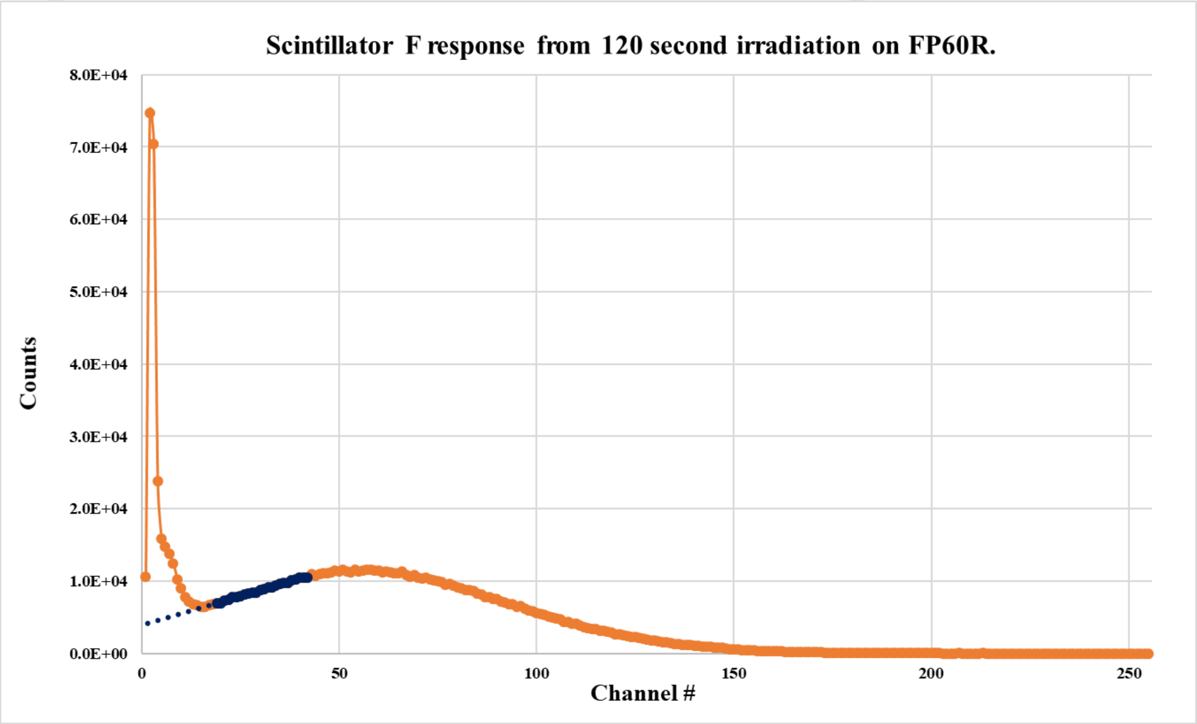
WNR FP60R Exposure Setup

FP60R Exposures on 10/19/19

	Irradiation Time (min)	Decay Time (min)	Count Time (min)	Dead Time (%)
Scintillator J	60	90	30	11.6
Scintillator F	15	65	30	12.71
Scintillator H	5	12	30	23.91



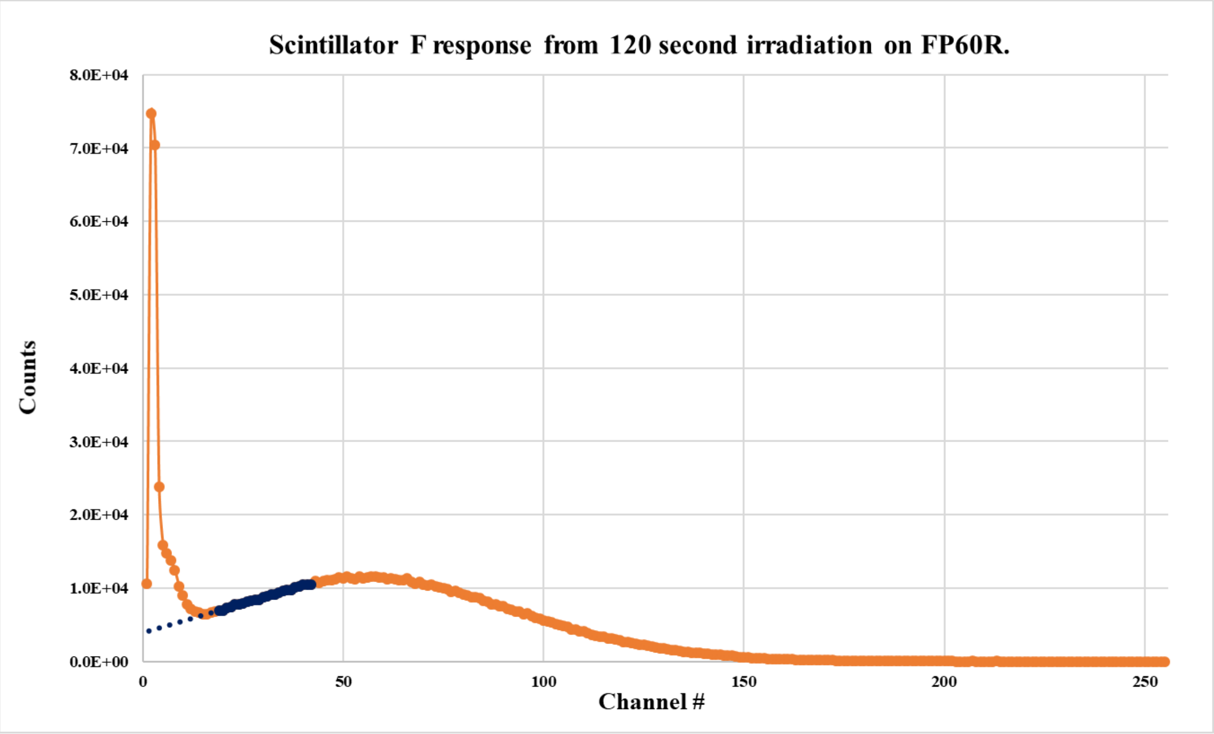
FP60R Exposures on 11/27/19



Gross counts Ch.(20-150) = 8.86×10^5

Dead time ~ 16% → CF(dead time) = 1.19

DT corrected Gross Counts Ch.(20-15) =1.053×10^6



$$CF(efficiency) = \frac{C_{20-150} + C_{0-20}}{C_{20-150}} = \frac{1.053x10^{6} + 1.29x10^{5}}{1.053x10^{6}} = 1.12$$

Field Measurements

FP30R Probe Field Measurements

Channel 3 Count Rates

	Average [cpm]	Average Background [cpm]
1x1 NaI	371.40	8.88
1x1 CsI	395.80	13.28
2x2 NaI	2044.00	76.27
2x2 CsI	2714.00	48.49

FP30R Field Measurements Cont.

- Placed in hot spot identified using the probes
- 45 min irradiation time
- 20 min transport/decay time
- 30 min real-time count time

Gross counts (20-150) = 5.21×10^4

DT Corrected gross counts 20-150) = 5.75×10^4

Background (20-150, 17 hour count) = 4.74×10^4

Net counts (20-150) = 1.02×10^4

CF(eff) = 1.12 → **N(counts) = 1.14×10^4**

FP30R Field Measurements Cont.

$$R_x(min^{-1}) = \frac{N(counts)}{\varepsilon \cdot \tau \cdot (1 - e^{-t_i/\tau}) \cdot (e^{-t_d/\tau}) \cdot (1 - e^{-t_c/\tau})}$$

$\boxed{R_x = 1.53x10^3 \text{ rxn/min} = 25.5 \text{ rxn/s}}$

$$\varphi\left(\frac{n}{cm^2 \cdot s}\right) = 9.94585\ x\ 10^{-3} * R_x(rxns/s)$$

$\boxed{= 15.26 \text{ n/cm}^2\text{s}}$

$$DE\left({}^{mrem}/_{h}\right) = CF(mrem/h\ per\ n/cm^2 \cdot s) * \varphi\left({}^{n}/_{cm^2 \cdot s}\right)$$

$\boxed{DE = 1.53 \text{ mrem/h}}$

FP30L Probe Field Measurements

60 min irradiation time
8 min transport/decay time
30 min count time

DE = 1.24 mrem/h

Conclusions

Sniffer Probe Conclusions

- All 4 probes are useable for qualitative surveys when:
  - Removed from very high intensity fields
  - Searching for fast and high-energy radiation, not necessarily with an exact 8 MeVee threshold

- Probes detect all radiations, not specific to neutrons
- The larger crystal size (2x2) increases sensitivity
- The CsI(Tl) material is preferable over the NaI(Tl) due to its density and atomic mass

Sniffer Probe Conclusions Cont.

- Using these probes to perform a shielding survey outside of WNR flightpaths, 2 locations were identified with elevated count rates where dose rates above background were measured
  - i.e., they work!

Plastic Scintillator Conclusions

- Dose quantification accomplished by measuring the $^{12}C(n,2n)^{11}C$ reaction taking place inside the plastic scintillators.
  - 4π counting system
  - Nearly 100% efficient
  - 20.4 MeV reaction threshold

- Performed measurements in two locations
  - FP30R: equating to 1.53 mrem/h
  - FP30L: equating to 1.24 mrem/h

Overall Conclusions

- Hot spots with dose rates as low as 1 mrem/h were easily located using the probes on ratemeter mode and relying on the audible assist feature
  - Indicates probes are highly sensitive
  - Are likely useable to even lower dose rates (0.1-0.2 mrem/h)
- Dose rates as low as 1 mrem/h in a continuously occupied area (2000 hours) are sufficient to reach the LANL ACL of 2 rem/yr

Future Work

- Pair probes to the more reliable and small RadEye SX ratemeters instead of E600s
- Compare plastic scintillator responses to the EAGLE and WENDII – are they similar?

Questions?

Birks' Law & MeVee

$$\frac{dL}{dE} = \frac{S}{1 + \left(kB * \frac{dE}{dX}\right)}$$

proton E[MeV]	dE/dX	dL/dE
8	24.33	98.3%
10	20.93	98.6%
20	12.88	99.1%
alpha E [MeV]		
8	235	85.9%
10	205.4	87.4%
20	133.4	91.5%

dL/dE = light output

S = scintillation efficiency = 1 when calibrated in MeVee

kB = quenching parameter = 7×10^{-4} g MeV^{-1} cm^{-2}

dE/dX = specific energy loss [MeV cm^2 g^{-1}] (found using NIST PSTAR, ESTAR, and ASTAR libraries)

FP60R Beam Parameters

Table 11. Initial beam parameters for FP60R on Oct. 19, 2019.

Parameter	Value
Distance from target to probe/scintillator faces	20 m
FP 60R Current	4.22 μA
Pulse Rate	100 pps
Pulse Envelope Length	625 μs

Table 15. Initial beam parameters for FP60R on Nov. 28, 2019.

Parameter	Value
Distance from target to probe/scintillator faces	20 m
FP60R Current	1.825 μA
Pulse Rate	100 pps
Pulse Envelope Length	625 μs

Table 12. Initial beam parameters for FP60R on Nov. 27, 2019.

Parameter	Value
Distance from target to probe/scintillator faces	20 m
FP60R Current	3.75 μA
Pulse Rate	100 pps
Pulse Envelope Length	625 μs

Table 16. Initial beam parameters for FP60R on Dec. 12, 2019.

Parameter	Value
Distance from target to probe/scintillator faces	20 m
FP 60R Current	3.763 μA
Pulse Rate	100 pps
Pulse Envelope Length	625 μs

Counting Cave Equipment List

Equipment	Model
Power Supply	ORTEC 4001M Mini-Bin Power Supply
High Voltage Power Supply	Tennelec TC952
Photomultiplier Tube	DuMont Electron Tubes 6364
Pre-amplifier	ORTEC 276
Amplifier	ORTEC 855 Dual Spec-Amp
Multi-Channel Analyzer	SpecTech Universal Spectrometer UCS20

Parameter	Value
Amplifier Output	+ Unipolar
Applied Voltage [kV]	+ 800
Course Gain	20
Fine Gain	6.0